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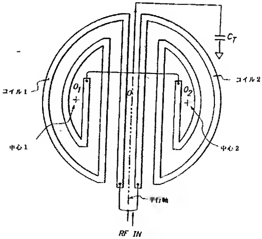
(54)【発明の名称】プラズマ発生装置

(57)【要約】　（修正有）

【課題】プラズマ反応器内で制御可能な均一な誘導結合を可能にするプラズマ発生装置の提供。

【解決手段】二重のコイル結合システムは平行なアンテナ・エレメントを使用する。2つのコイル（コイル1およびコイル2）は対称的であり、コイルの各ループは半円と平行とのアンテナ・エレメントからなる。RFは各コイル（平行軸により近い）の平行エレメントの中央に同時に供給され、コイルの他の端部は結合され、コンデンサC_Tを介して接地に終端される。

【選択図】図7



【特許請求の範囲】
【請求項1】
誘導結合型プラズマを発生させるための装置であって、
チャンバ中に電磁界経路を形成するウィンドウと該チャンバ中にプロセス・ガスを導入するように構成されたプロセス・ガス供給源とを有するプラズマ反応チャンバと、
前記チャンバのウィンドウに近接して配設された少なくとも第１および第２のアンテナ・セグメントを含む高周波アンテナと、前記アンテナ・セグメントに結合され、前記アンテナ・セグメント中の高周波電流を共振させるように構成された高周波発生源と、を備え、
前記高周波電流によって誘導された電磁界は、前記ウィンドウを通過し、プロセス・ガスを励起してイオン化し、それによりチャンバ内にプラズマを発生させ、かつ、
前記第１のアンテナ・セグメントが、前記第２のアンテナ・セグメントを取り囲んでいることを特徴とする装置。
【請求項2】
発生するプラズマの密度が、前記少なくとも第１および第２のアンテナ・セグメントがまたがる領域内で実質的に均一であることを特徴とする請求項１に記載の装置。
【請求項3】
前記少なくとも第１および第２のアンテナ・セグメントが、それぞれ、高周波電力を前記チャンバ中の異なる領域に結合し、これにより、前記チャンバ中に全体的に均一なプラズマを発生させることを特徴とする請求項１に記載の装置。
【請求項4】
前記少なくとも第１および第２のアンテナ・セグメントが、単巻コイルからなることを特徴とする請求項１に記載の装置。
【請求項5】
前記第１のアンテナ・セグメントが単巻コイルからなり、前記第２のアンテナ・セグメントが複巻コイルからなることを特徴とする請求項１に記載の装置。
【請求項6】
前記少なくとも第１および第２のアンテナ・セグメントが、複巻コイルからなることを特徴とする請求項１に記載の装置。
【請求項7】
更に、同じ電流又は異なる電流が得られるように、前記少なくとも第１および第２のアンテナ・セグメントの電流を調整するための少なくとも１つの入力側調整コンデンサを含むことを特徴とする請求項１に記載の装置。
【請求項8】
前記少なくとも１つの入力側調整コンデンサが、
各々の前記アンテナ・セグメントにより大きい電流を供給し、これにより前記アンテナ・セグメントに隣接するプラズマ領域への高周波電力結合がより大きくなるか、又は、
各々の前記アンテナ・セグメントにより小さい電流を供給し、これにより前記プラズマ領域への電力結合がより小さくなることを特徴とする請求項７に記載の装置。
【請求項9】
一対のアンテナ・セグメントの電流を調整するために一対の入力側コンデンサが使用され、それらが１回の制御により反対方向に回転されるように構成されていることを特徴とする請求項７に記載の装置。
【請求項10】
前記少なくとも第１および第２のアンテナ・セグメントが単一の高周波電力源によって電力供給され、単一の整合回路網によって調整されることを特徴とする請求項１に記載の装置。
【請求項11】
第１および第２のアンテナ・セグメントの出力端部が結合され、インピーダンスを介し

て接地に終端されていることを特徴とする請求項１に記載の装置。
【請求項12】
前記第１および第２のアンテナ・セグメントの出力端部が、別個の出力側固定コンデンサまたは出力側可変コンデンサを介して接地に終端されていることを特徴とする請求項１に記載の装置。
【請求項13】
各々の出力コンデンサが、各アンテナ・セグメントに沿った電流極値または電圧極値の場所を調整することを特徴とする請求項１２に記載の装置。
【請求項14】
前記第１および第２のアンテナ・セグメントにおける最大電流の場所が、第２のアンテナ・セグメントに対する第１のアンテナ・セグメントの回転位置によって決まり、
前記出力側コンデンサは、さらに、電流最大値の場所が方位角的に約１８０度離れ、かつ半径方向に互いに対向するように前記場所を調整し、それにより方位角不均一電流分布によるプラズマ方位角不均一性を大幅に低減することを特徴とする請求項１２に記載の装置。
【請求項15】
一対の出力コンデンサが前記第１および第２のアンテナ・セグメント中の電流を調整し、それらは１回の制御により反対方向に回転されるように構成されていることを特徴とする請求項１２に記載の装置。
【請求項16】
前記第１および第２のアンテナ・セグメントは、同一平面内にある二次元構成、非平面的な三次元構成、またはその組合せで構成されていることを特徴とする請求項１に記載の装置。
【請求項17】
前記第１および第２のアンテナ・セグメントが同心状に構成されており、一方の前記アンテナ・セグメントが他方の前記アンテナ・セグメントよりも小さい直径を有することを特徴とする請求項１に記載の装置。
【請求項18】
前記三次元構成が、ドーム状又はらせん状であることを特徴とする請求項１６に記載の装置。
【請求項19】
各々の前記アンテナ・セグメントの形状が、ほぼ円形であることを特徴とする請求項１に記載の装置。
【請求項20】
前記少なくとも第１および第２のアンテナ・セグメントが、前記チャンバのウィンドウの外表面に近接して配置されていることを特徴とする請求項１に記載の装置。
【請求項21】
前記第１および第２のアンテナ・セグメントの電流が前記セグメントの周りに同じ方位角方向に流れることを特徴とする請求項１に記載の装置。
【請求項22】
誘導結合型プラズマを発生させるための装置であって、
チャンバ中に電磁界経路を形成するウィンドウと、前記チャンバ中にプロセス・ガスを導入するように構成されたプロセス・ガス供給源とを有するプラズマ反応チャンバと、前記チャンバのウィンドウに近接して配置された少なくとも第１および第２の複巻アンテナ・セグメントを含む高周波アンテナと、
前記アンテナ・セグメントに結合され、前記アンテナ・セグメント中の高周波電流を共振させるように構成された高周波発生源と、を備え、前記高周波電流によって誘導された電磁界は、前記ウィンドウを通過し、プロセス・ガスを励起してイオン化し、それにより前記チャンバ内にプラズマを発生させ、また、
前記第１の複巻アンテナ・セグメントが、前記第２の複巻アンテナ・セグメントを取り

囲む外側コイルであることを特徴とする装置。

【請求項23】

発生したプラズマの密度が、前記第１および第２の複巻アンテナ・セグメントがまたがる領域で実質的に均一であることを特徴とする請求項２２に記載の装置。

【請求項24】

前記少なくとも第１および第２のアンテナ・セグメントのが、それぞれ高周波電力を前記チャンバ中の異なる領域に結合し、これにより前記チャンバ中に全体的な均一なプラズマが発生させせることを特徴とする請求項２２に記載の装置。

【請求項25】

前記第１の複巻アンテナ・セグメントが平面的な複巻コイルとして構成されており、前記第２の複巻アンテナ・セグメントが第１および第２の部分を有することを特徴とする請求項２２に記載の装置。

【請求項26】

前記第２の複巻アンテナ・セグメントの前記第１の部分が平面的な複巻コイルとして構成されており、前記第２の複巻アンテナ・セグメントの前記第２の部分がらせん状のコイルとして構成されていることを特徴とする請求項２５に記載の装置。

【請求項27】

前記第２の部分には、さらに、前記らせん状のコイル内に中空の誘電体シリンダが設けられ、該中空の誘電体シリンダの中空領域が前記プロセス・チャンバに直接接続されていることを特徴とする請求項２６に記載の装置。

【請求項28】

前記らせん状のコイルと前記中空の誘電体シリンダは、プラズマが、前記チャンバ内で、より低い圧力で当たるように構成されており、これにより前記プロセス・チャンバの中心部におけるプラズマ密度が高くなることを特徴とする請求項２７に記載の装置。

【請求項29】

前記第１の複巻アンテナ・セグメントが、第１の平面的な部分と第２の非平面的な部分とを有し、前記第２の複巻アンテナ・セグメントが第１の平面的な部分と第２の非平面的な部分とを有することを特徴とする請求項２２に記載の装置。

【請求項30】

前記第１の複巻アンテナ・セグメントの前記第２の部分が、らせん状のコイルとして構成されていることを特徴とする請求項２９に記載の装置。

【請求項31】

前記第２の複巻アンテナ・セグメントの前記第２の部分が、らせん状のコイルとして構成されていることを特徴とする請求項２９に記載の装置。

【請求項32】

前記第１の複巻アンテナ・セグメントの全長が、第２の複巻アンテナ・セグメントの全長と同等であり、それにより前記アンテナ・セグメント中の電流が、より大きい程度まで調整されることを特徴とする請求項２２に記載の装置。

【請求項33】

更に、同じ電流又は異なる電流が得られるように、前記少なくとも第１および第２のアンテナ・セグメント内の電流を調整するための少なくとも１つの入力側調整コンデンサを含むことを特徴とする請求項２２に記載の装置。

【請求項34】

前記少なくとも１つの入力側調整コンデンサが、

各アンテナ・セグメントにより大きい電流を供給し、これにより前記アンテナ・セグメントに隣接するプラズマ領域への高周波電力結合がより大きくなるか、又は、

各アンテナ・セグメントにより小さい電流を供給し、これにより前記プラズマ領域への電力結合がより小さくなることを特徴とする請求項３３に記載の装置。

【請求項35】

前記第１および第２のアンテナ・セグメント中の電流を調整するために一対の入力側コ

ンデンサが使用され、それらが１回の制御により反対方向に回転されるように構成されていることを特徴とする請求項３３に記載の装置。

【請求項36】

前記少なくとも第１および第２のアンテナ・セグメント、が単一の高周波電力源によって電力供給され、単一の整合回路網によって調整されることを特徴とする請求項２２に記載の装置。

【請求項37】

前記第１および第２のアンテナ・セグメントの出力端部が、別個の出力側固定コンデンサまたは出力側可変コンデンサを介して接地に終端されていることを特徴とする請求項２２に記載の装置。

【請求項38】

各出力コンデンサが、各アンテナ・セグメントに沿った電流極値または電圧極値の場所を調整することを特徴とする請求項３７に記載の装置。

【請求項39】

前記第１および第２のアンテナ・セグメントにおける電流最大値の場所が、前記第２のアンテナ・セグメントに対する前記第１のアンテナ・セグメントの回転位置によって決まり、

前記出力側コンデンサは、さらに、電流最大値の場所が方位角的に約１８０度離れ、かつ半径方向に互いに対向するように前記場所を調整し、それにより方位角不均一電流分布によるプラズマ方位角不均一性を大幅に低減することを特徴とする請求項３７に記載の装置。

【請求項40】

前記第１および第２のアンテナ・セグメント中の電流を調整するための一対の出力コンデンサが使用され、それらが１回の制御により反対方向に回転されるように構成されていることを特徴とする請求項３７に記載の装置。

【請求項41】

電流最大値の場所を、前記第２の複巻アンテナ・セグメントの前記第１の部分か又は前記第２の部分にシフトするための出力側コンデンサが使用され、これにより前記複巻アンテナ・セグメントから前記プラズマへの電力結合に変化が生じることを特徴とする請求項２６に記載の装置。

【請求項42】

電流最大値の場所を、前記第２の複巻アンテナ・セグメントの前記第１の部分か又は前記第２の部分にシフトするための出力側コンデンサが使用され、これにより前記複巻アンテナ・セグメントから前記プラズマへの電力結合に変化が生じることを特徴とする請求項３０に記載の装置。

【請求項43】

電流最大値の場所を第２の複巻アンテナ・セグメントの第１の部分かまたは第２の部分にシフトするために出力コンデンサが使用され、その結果、複巻アンテナ・セグメントからプラズマへの電力結合に変化が生じることを特徴とする請求項３１に記載の装置。

【請求項44】

さらに、前記出力側コンデンサに関連する入力側コンデンサを含み、

前記入力側コンデンサの調整の結果、高周波数の全入力インピーダンスが比較的不変に維持され、それにより一方の複巻アンテナ・セグメント中の電流が他方の複巻アンテナ・セグメント中の電流に影響を及ぼさなくなることを特徴とする請求項４１に記載の装置。

【請求項45】

さらに、前記出力側コンデンサに関連する入力側コンデンサを含み、

前記入力コンデンサの調整の結果、高周波数の全入力インピーダンスが比較的不変に維持され、それにより一方の複巻アンテナ・セグメント中の電流が他方の複巻アンテナ・セグメント中の電流に影響を及ぼさなくなることを特徴とする請求項４２に記載の装置。

【請求項46】

さらに、前記出力側コンデンサに関連する入力側コンデンサを含み、前記入力側コンデンサの調整の結果、高周波数の全入力インピーダンスが比較的不変に維持され、それにより一方の複巻アンテナ・セグメント中の電流が他方の複巻アンテナ・セグメント中の電流に影響を及ぼさなくなることを特徴とする請求項４３に記載の装置。

【請求項47】

前記第１および第２のアンテナ・セグメントが同心状に構成されており、一方の前記アンテナ・セグメントが他方の前記アンテナ・セグメントよりも小さい直径を有することを特徴とする請求項２２に記載の装置。

【請求項48】

前記少なくとも第１および第２のアンテナ・セグメントが前記チャンバのウィンドウの外表面に近接して配置されていることを特徴とする請求項２２に記載の装置。

【請求項49】

前記第１および第２のアンテナ・セグメント内の電流が前記セグメントの周りに同じ方位角方向に流れることを特徴とする請求項２２に記載の装置。

【請求項50】

誘導結合型プラズマを発生させるための装置であって、

チャンバ中に電磁界経路を形成するウィンドウと、該チャンバ中にプロセス・ガスを導入するように構成されたプロセス・ガス供給源とを有するプラズマ反応チャンバと、

前記チャンバのウィンドウに近接して配置された同様の形状の２つのアンテナ・セグメントを含む高周波アンテナと、前記アンテナ・セグメントに結合され、前記アンテナ・セグメント中の高周波電流を共振させるように構成された高周波発生源と、を備え、

前記高周波電流によって誘導された電磁界は、前記ウィンドウを通過し、プロセス・ガスを励起してイオン化し、それにより前記チャンバ内にプラズマを発生させ、また、

前記２つのアンテナ・セグメントが離間し、中心軸の周りに対称に配置されていることを特徴とする装置。

【請求項51】

各アンテナ・セグメントがＤ字形であり、半円とその直径に略沿った直線とから構成されていることを特徴とする請求項５０に記載の装置。

【請求項52】

前記アンテナ・セグメントの直線が互いに平行であり、前記ウィンドウの中心領域を覆い、これにより前記中心軸の周りに対称的なプラズマ密度が生じることを特徴とする請求項５１に記載の装置。

【請求項53】

前記２つのアンテナ・セグメントの入力端部が結合され、また、

前記２つのアンテナ・セグメントの出力端部が結合され、かつ、可変コンデンサを介して接地に終端されていることを特徴とする請求項５０に記載の装置。

【請求項54】

前記２つのアンテナ・セグメントの前記直線中の電流が同じ方向に流れることを特徴とする請求項５１に記載の装置。

【請求項55】

前記アンテナ・セグメントが単一の高周波電力源によって電力供給され、単一の整合回路網によって調整されることを特徴とする請求項５０に記載の装置。

【請求項56】

発生したプラズマの密度が、前記アンテナ・セグメントがまたがる領域内で実質的に均一であることを特徴とする請求項５０に記載の装置。

【請求項57】

前記アンテナ・セグメントが、それぞれ、高周波電力を前記チャンバの異なる領域中に結合し、これにより前記チャンバ中に全体的に均一なプラズマが生じることを特徴とする請求項５０に記載の装置。

【請求項58】

前記アンテナ・セグメントが、前記チャンバのウィンドウの外表面に近接して配置されていることを特徴とする請求項５０に記載の装置。
【請求項59】
プラズマ反応チャンバ用の誘導結合型プラズマ・アンテナ・システムであって、
離間した第１および第２の同心電流経路を備え、
前記同心電流経路内の電流が、同じ方向に流れることを特徴とするシステム。
【請求項60】
前記同心電流経路が、高周波電力を、前記チャンバ中の半径方向及び方位角的に異なる領域に結合し、かつ、前記チャンバ中で均一なプラズマ分布が得られるように協働することを特徴とする請求項５９に記載の装置。
【請求項61】
前記同心電流経路が、共面二次元構成、非平面的な三次元構成、またはその組合せで構成されていることを特徴とする請求項５９に記載の装置。
【請求項62】
半導体基板の露出した表面を、請求項１に記載の装置中で形成されたプラズマに接触させることによって処理する方法。
【請求項63】
半導体基板の露出した表面を、請求項２２に記載の装置中で形成されたプラズマに接触させることによって処理する方法。
【請求項64】
半導体基板の露出した表面を、請求項５０に記載の装置中で形成されたプラズマに接触させることによって処理する方法。
【請求項65】
半導体基板の露出した表面を、請求項５９に記載の装置中で形成されたプラズマに接触させることによって処理する方法。
【発明の詳細な説明】
【技術分野】
【0001】
本発明は、半導体基板などの材料を処理するためのプラズマ反応器に関する。より詳細には、本発明は、プラズマ反応器内の誘導結合均一性を改善するためのシステムに関する。
【背景技術】
【0002】
プラズマの発生は様々な半導体製造プロセス、例えばプラズマ・エッチング及び堆積において有用である。プラズマは一般に、個々の電子ガス分子衝突による運動エネルギーの伝達によって個々のガス分子をイオン化させる自由電子の電界イオン化および生成によって低圧ガスから生成される。電子は通常、電界、一般には高周波電界の中で加速される。
【0003】
ＲＦ電界中の電子を加速するための多数の技法が提案されている。例えば、米国特許第４９４８４５８号には、処理すべき半導体ウエハの平面的なに平行に位置する平面的なアンテナ・コイルを使用して、チャンバ内の高周波電界中で電子を励起するプラズマ発生デバイスが開示されている。図１に、アンテナ・システム１０５、誘電体ウィンドウ１２０、ガス分配プレート１３０、処理すべきウエハ１４０、真空チャンバ１５０、静電チャック１６０、および下側電極１７０を含んでいるプラズマ発生デバイス１００を概略的に示す。
【0004】
動作に際しては、高周波発生源（図示せず）を使用して、一般に高周波整合回路（図示せず）を介して、アンテナ・システム１０５に高周波電流を供給する。高周波電流は、一般にアンテナ・システム１０５を介して共振し、真空チャンバ１５０内で方位角電界を誘導する。同時に、ガス分配プレート１３０を介してプロセス・ガスを真空チャンバ１５０中に導入すると、誘導された電界によりプロセス・ガスがイオン化してチャンバ１５０内

にプラズマが生成される。次いでプラズマは、（静電チャック１６０によって所定の位置に保持された）ウエハ１４０に当たり、ウエハ１４０を必要に応じて処理する（例えば、エッチングする）。一般に、アンテナ・コイルに加えられる周波数とは異なる周波数である別の高周波数を下側電極１７０に加えて、イオン衝撃用の負のＤＣバイアス電圧を得る。

【0005】

図２Ａおよび図２Ｂに、米国特許第４９４８４５８号に示されているアンテナ・システムを構成する２つの渦巻き状の平面的なコイル１１０ａ、１１０ｂを示す。図２Ａに示すように、第１の平面的なコイル１１０ａは、平面的なスパイラルに形成された一つの導電エレメントとして構成され、高周波回路への接続のために高周波タップ２０５、２１５に接続されている。図２Ｂでは、別の平面的なコイル１１０ｂは、相互接続２２５を介して直列に接続された複数の接続リング２２０として構成され、各端部が高周波タップ２０５、２１５に接続されている。

【0006】

当技術分野においてよく知られているように、そのような渦巻き状のコイルによって得られる円状電流パターンはドーナツ形プラズマを作り出し、これによりウエハ１４０におけるエッチング速度に半径方向の不均一性が生じることがある。言い換えれば、平面的なコイル・アンテナ１１０によって誘導的に発生する電界は、一般に、（半径方向成分Ｅｒ＝０および方位角成分Ｅθ≠０を有する）方位角電界であるが、中心部では０である（Ｅｒ＝０およびＥθ≠０）。したがって、コイル・アンテナ１１０は、中心部においてより低い密度を有するドーナツ形プラズマを生成するので、ドーナツの中心部において適切な均一性を得るためには、プラズマ拡散（すなわち、中心部への電子およびイオンの拡散）を利用しなければならない。ただし、用途によっては、プラズマ拡散によって得られる均一性は不十分である。

【0007】

さらに、そのような渦巻き状のコイル・アンテナは方位角不均一プラズマをつくる傾向がある。これは、平面的なアンテナ・コイルを構成するために使用される結合線路の比較的長い長さが、コイルが一般に動作する高周波数においてかなりの電気的長さを有することに起因する。電圧波および電流波は入力端部から端子端部まで順方向に進行し、端子端部において再び反射されることになる。順方向波および反射波の重ね合わせの結果、コイルに定在波が生じる（すなわち、電圧および電流がコイルの長さに沿って周期的に変化する）。コイルを端子端部において接地した場合、端子端部における電流は最大値になり、端子端部における電圧は０になる。入力に向かってコイルに沿って進むと、電圧は増大し、電流は減少し、ついには電気的長さが９０度のところで、電圧は最大値になり、電流は最小値になる。そのようなある程度の変化があると、極めて不均一なプラズマが生じる。したがって、平面的なコイルは一般にキャパシタンスで終端され、それによりコイル中の電流はコイルの両端部において同じになり、コイルの中央部の近くで最大値まで増大する。そうするとプラズマ均一性を改善することができるが、電流がコイルの長さに沿って方位角方向に変化するので、方位角不均一性はまだ存在する。例えば、図２Ａの点Ｐは電流最大値である。点Ｐのいずれかの側で、電流は低下する。したがって、プラズマに結合する電力はＰの下でより大きくなり、対応するプラズマはより密になる。反対に、点Ｐ’におけるプラズマ密度は比較的低くなる。

【0008】

終端コンデンサ値は変化させることができるが、そうするとコイルに沿った電圧の位置が変化するだけであることに留意されたい。さらに、コイル長さに沿って同じ極性の電圧を得るためにコイルをインダクタンスで終端させることができるが、コイルの中心位置のどこかに電流ゼロが存在することになり（電流はゼロのいずれかの側で反対方向に流れる）、生じたプラズマ密度は容認できないほど低くかつ不均一になることがある。Ｐａｔｒｉｃｋ他の米国特許第５４０１３５０号は上述の欠点を克服しようと試みるものである。そこには、プラズマ均一性を改善するための複数平面的なコイル構成が記載されている。

個々のコイルへのＲＦ電力は独立して制御され、電力および位相の独立した調整に対処する別個の電力源および別個の整合回路網が必要となる。

【0009】

プラズマ結合システム内で誘導結合均一性を制御するための改善された方法および装置が必要であることは明らかである。

【図面の簡単な説明】

【0013】

【図1】処理チャンバ中に高周波エネルギーを結合するために使用される誘電体ウィンドウの上部にアンテナ・システムが置かれているプラズマ反応器を示す図である。

【図2A】従来の渦巻き状の平面的なコイル・アンテナを示す図である。

【図2B】別の従来の渦巻き状の平面的なコイル・アンテナを示す図である。

【図3】本発明の第１の実施形態による二重の平面的な単巻コイルの構成例を示す図である。

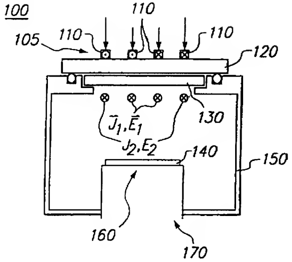
【図4】本発明の第２の実施形態による二重の平面的な複巻コイルの構成例を示す図である。

【図5】本発明の第３の実施形態による、内側にらせん状のコイルをもつ二重の平面的な複巻コイルの構成例を示す図である。

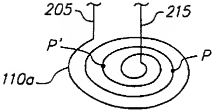
【図6】本発明の第４の実施形態による、内側及び外側の両方にらせん状のコイルを有する二重の平面的な複巻コイルの例示的な構成を示す図である。

【図7】本発明の第５の実施形態による、平行アンテナ・エレメントをもつ二重の平面的な複巻コイルの構成例を示す図である。

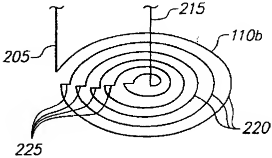
【図1】



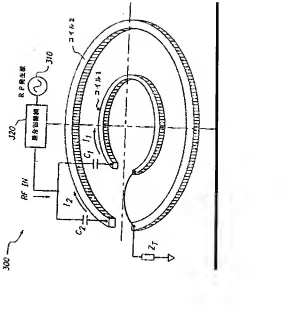
【図2A】



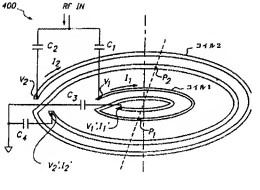
【図2B】



【図3】



【図4】



【図5】

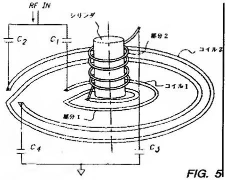
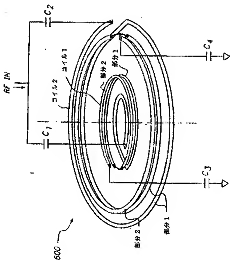
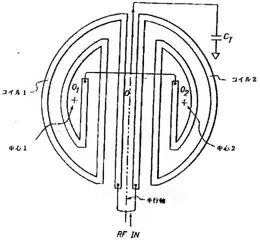


FIG. 5

【図6】



【図7】



【手続補正書】
【提出日】平成21年8月6日(2009.8.6)
【手続補正1】
【補正対象書類名】特許請求の範囲
【補正対象項目名】全文
【補正方法】変更
【補正の内容】
【特許請求の範囲】
【請求項1】
誘導結合型プラズマを発生させるための装置であって、
チャンバ中に電磁界経路を形成するウィンドウと、該チャンバ中にプロセス・ガスを導入するように構成されたプロセス・ガス供給源とを有するプラズマ反応チャンバと、
前記チャンバのウィンドウに近接して配置された同様の形状の２つのアンテナ・セグメントを含む高周波アンテナと、
前記アンテナ・セグメントに結合され、前記アンテナ・セグメント中の高周波電流を共振させるように構成された高周波発生源と、を備え、
前記高周波電流によって誘導された電磁界は、前記ウィンドウを通過し、プロセス・ガスを励起してイオン化し、それにより前記チャンバ内にプラズマを発生させ、また、
前記２つのアンテナ・セグメントが離間し、前記２つのアンテナ・セグメント間の中心軸に対して対称に配置されていることを特徴とする装置。
【請求項2】
各アンテナ・セグメントがＤ字形であり、半円とその直径に略沿った直線とから構成されていることを特徴とする請求項１に記載の装置。
【請求項3】
前記アンテナ・セグメントの直線が互いに平行であり、前記ウィンドウの中心領域を覆い、これにより前記中心軸の周りに対称的なプラズマ密度が生じることを特徴とする請求項２に記載の装置。
【請求項4】
前記２つのアンテナ・セグメントの入力端部が結合され、また、
前記２つのアンテナ・セグメントの出力端部が結合され、かつ、可変コンデンサを介して接地に終端されていることを特徴とする請求項１に記載の装置。
【請求項5】
前記２つのアンテナ・セグメントの前記直線中の電流が同じ方向に流れることを特徴とする請求項２に記載の装置。
【請求項6】

前記アンテナ・セグメントが単一の高周波電力源によって電力供給され、単一の整合回路網によって調整されることを特徴とする請求項１に記載の装置。
【請求項7】
発生したプラズマの密度が、前記アンテナ・セグメントがまたがる領域内で実質的に均一であることを特徴とする請求項１に記載の装置。
【請求項8】
前記アンテナ・セグメントが、それぞれ、高周波電力を前記チャンバの異なる領域中に結合し、これにより前記チャンバ中に全体的に均一なプラズマが生じることを特徴とする請求項１に記載の装置。
【請求項9】
前記アンテナ・セグメントが、前記チャンバのウィンドウの外表面に近接して配置されていることを特徴とする請求項１に記載の装置。

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【外国語明細書】

【図7】

MULTIPLE COIL ANTENNA FOR INDUCTIVELY-COUPLED PLASMA GENERATION SYSTEMS

Field of the Invention

The present invention relates to plasma reactors for processing materials such as semiconductor substrates. More particularly, the present invention relates to a system for improving the inductive coupling uniformity within plasma reactors.

Background of the Invention

Plasma generation is useful in a variety of semiconductor fabrication processes, for example plasma enhanced etching and deposition. Plasmas are generally produced from a low pressure gas by electric field ionization and generation of free electrons which ionize individual gas molecules through the transfer of kinetic energy via individual electron-gas molecule collisions. The electrons are commonly accelerated in an electric field, typically a radio frequency electric field.

Numerous techniques have been proposed to accelerate the electrons in an RF electric field. For example, U.S. Patent No. 4,948,458 discloses a plasma generating device in which electrons are excited in a radio frequency field within a chamber using a planar antenna coil that is situated parallel to the plane of a semiconductor wafer to be processed. Figure 1 schematically illustrates a plasma generating device 100 which includes an antenna system 105, a dielectric window 120, a gas distribution plate 130, a wafer to be processed 140, a vacuum chamber 150, an electrostatic chuck 160, and a lower electrode 170.

In operation, a radio frequency source (not shown) is used to provide a radio frequency current to the antenna system 105, typically via a radio frequency matching circuit (also not shown). The radio frequency current resonates through the antenna system 105, inducing an azimuthal electric field within the vacuum chamber 150. At the same time, a process gas is introduced into the vacuum chamber 150 via the gas distribution plate 130, and the induced electric field

ionizes the process gas to produce a plasma within the chamber 150. The plasma then impinges upon the wafer 140 (which is held in place by way of the electrostatic chuck 160) and processes (e.g., etching) the wafer 140 as desired. Another radio frequency, at a frequency which is different from that applied to the antenna coil, is typically applied to the lower electrode 170 to provide a negative DC bias voltage for ion bombardment.

Figures 2A and 2B depict two planar spiral coils 110a, 110b which make up the antenna system illustrated in the '458 patent. As shown in Figure 2A, a first planar coil 110a is constructed as a singular conductive element formed into a planar spiral and connected to radio frequency taps 205, 215 for connection to radio frequency circuitry. In Figure 2B, an alternative planar coil 110b is constructed as a plurality of concentric rings 220 connected in series via inter-connectors 225 and coupled at each end to radio frequency taps 205, 215.

As is well known in the art, the circular current pattern provided by such spiral coils creates toroidal-shaped plasmas which can in turn cause radial non-uniformity in the etch rate at the wafer 140. In other words, the E-field inductively generated by the planar coil antenna 110 is generally azimuthal (having a radial component $E_r = 0$ and an azimuthal component $E_\theta \neq 0$), but zero at the center ($E_r = 0$ and $E_\theta = 0$). Thus, the coil antenna 110 produces a toroidal plasma having a lower density in the center, and must rely on plasma diffusion (i.e., the diffusion of electrons and ions into the center) in order to provide reasonable uniformity at the center of the toroid. In certain applications, however, the uniformity provided by plasma diffusion is insufficient.

Further, such spiral coil antennas tend to make azimuthal non-uniform plasma. This results from the fact that the relatively long lengths of coupling lines used to construct the planar antenna coils have significant electrical lengths at the radio frequency at which they typically operate. The voltage and current waves travel forward from the input end to the terminal end, and will be reflected back at the terminal end. The superposition of the forward and reflected waves results in

a standing wave on the coil (i.e., the voltage and current vary periodically along the length of the coil). If the coil is grounded at the terminal end, the current at the terminal end is at a maximum value, and the voltage at the terminal end is zero. Proceeding along the coil toward the input, the voltage increases and the current decreases until, at 90 degrees of electrical length, the voltage is at a maximum and the current is at a minimum. Such a degree of variation results in a highly non-uniform plasma. Consequently, the planar coil is typically terminated with a capacitance such that the current in the coil is similar at both ends of the coil and increases to a maximum near the middle of the coil. Doing so can improve plasma uniformity, but azimuthal non-uniformity still exists because the current varies in the azimuthal direction along the length of the coil. For example, point P in Figure 2A is the current maximum. On either side of point P the current drops off. Therefore, the power coupling to the plasma is higher beneath P and the corresponding plasma is denser. In contrast, the plasma density at point P' is relatively lower.

Note that, although the terminating capacitor value can be varied, doing so only changes the position of the voltage null along the coil. Further, although the coil can be terminated with an inductance in order to provide the same polarity voltage along the coil length, a current null will exist somewhere in the central portion of the coil (with the current traveling in opposite directions on either side of the null), and the resulting plasma density can be unacceptably low and non-uniform. U.S. Patent No. 5,401,350 to Patrick et al. attempts to overcome the above-described deficiencies. Therein, a multiple planar coil configuration is set forth in order to improve plasma uniformity. The RF power to the individual coils is independently controlled, requiring separate power supplies and separate matching networks which allow for independent adjustment of the power and phase.

It is evident that a need exists for improved methods and apparatuses for controlling the inductive coupling uniformity within a plasma coupled system.

Summary of the Invention

The present invention overcomes the above-identified deficiencies in the art by providing a system for improving the inductive coupling uniformity within an antenna system. By controlling the positioning and current distribution of the antenna coils, plasma uniformity can be improved.

According to exemplary embodiments, two or more spiral coils are positioned on a dielectric window of a plasma chamber. Each coil is either planar or a combination of both a planar coil and a vertically stacked helical coil. The input end of each coil is attached to an input variable capacitor and the output end is terminated to the ground through an output variable capacitor. The output capacitor determines where the current is an extreme (i.e., a maximum or a minimum) or the voltage is an extreme, while the input capacitor can change the overall impedance of each coil, and therefore, the ratio of current magnitudes in these multiple coils can be adjusted. By adjusting the magnitude of the current and the location of the maximum current in each coil, plasma density, and therefore, plasma uniformity, can be controlled.

The above-described and other features and advantages of the present invention are explained in detail hereinafter with reference to the illustrative examples shown in the accompanying drawings. Those skilled in the art will appreciate that the described embodiments are provided for purposes of illustration and understanding and that numerous equivalent embodiments are contemplated herein.

Brief Description of the Drawings

Figure 1 depicts a plasma reactor wherein an antenna system is placed at the top of the dielectric window and is used to couple radio frequency energy into a processing chamber;

Figures 2A and 2B depict two conventional planar spiral coil antennas;

Figure 3 depicts an exemplary arrangement of dual, single-turn planar coils according to a first embodiment of the present invention;

Figure 4 depicts an exemplary arrangement of dual, multiple-turn planar coils according to a second embodiment of the present invention;

Figure 5 depicts an exemplary arrangement of dual, multiple-turn planar coils with an inner helical coil according to a third embodiment of the present invention;

Figure 6 depicts an exemplary arrangement of dual, multiple-turn planar coils, with both inner and outer helical coils according to a fourth embodiment of the present invention; and

Figure 7 depicts an exemplary arrangement of dual, multiple-turn planar coils with parallel antenna elements according to a fifth embodiment of the present invention.

Detailed Description of the Invention

Figure 1 depicts a plasma generating device 100 in which the antenna system of the present invention may be incorporated. As discussed above, the plasma generating device 100 includes a dielectric window 120, a gas distribution plate 130, a wafer 140, a vacuum chamber 150, an electrostatic chuck 160, a lower electrode 170 and an antenna system 105. The antenna system 105 includes a set of coils 110 which is connected to a RF matching network (not shown) and a RF generator (not shown).

According to exemplary embodiments of the present invention, the antenna system is a Transformer-Coupled Plasma (TCP™, a registered trademark of Lam Research Corporation) antenna system. Figure 3 illustrates the TCP™ antenna system 300 according to a first embodiment of the present invention. In this embodiment, the TCP™ system 300 includes two single-turn coils. Coil 1 is preferably placed near the center while Coil 2 is preferably placed further toward the outer edge of the reactor's top opening. A radio frequency (RF) current is

simultaneously provided to one end of Coils 1 and 2 via two tuning capacitors C_1 and C_2. As is well known in the art, the RF input is generated by a RF source 310 and fed to capacitors C_1 and C_2 through a RF matching network 320. Tuning capacitors C_1 and C_2 allow for the magnitude of currents I_1 and I_2 in Coils 1 and 2, respectively, to be adjusted. The opposite ends of Coil 1 and Coil 2 are tied together and terminated to ground through impedance Z_T.

The electric field that is inductively generated by a single-turn, planar coil is azimuthal (the radial component $E_r = 0$ and an azimuthal component $E_\theta \neq 0$) but zero at the center ($E_r = 0$ and $E_\theta = 0$). Near the dielectric window surface, the induced E-field and induced current ($J = \sigma E$) in the plasma are almost mirror images of the driving coil. A planar coil antenna produces a toroidal plasma with a radius which is close to one half of the driving coil's radius. By placing two coils apart, this effectively generates a more gradual plasma toroid having a radius that is approximately equal to one half of the mean radii of the two coils. The power coupling to the plasma from the inner coil is localized in the inner region while the power coupling from the outer coil is localized in the outer region. As a result, plasma diffusion (i.e., the diffusion of electrons and ions) tends to make the plasma density more uniform in the center and elsewhere.

As indicated above, the circuitry associated with the two single-turn coils (i.e., the capacitors C_1 and C_2 and impedance Z_T) is capable of adjusting the ratio of current magnitudes in Coil 1 and Coil 2, i.e., I_1 and I_2, respectively. By adjusting the ratio of current magnitudes, the plasma uniformity between the reactor's center and the edge can be adjusted. As will be appreciated by one skilled in the art, C_1 and C_2 may be either fixed or variable capacitors.

Input tuning capacitors C_1 and C_2 partially cancel the input inductive reactance of each coil. With a proper choice of the values for C_1 and C_2, the input reactance of each leg is the same, resulting in equal input currents into Coil 1 and Coil 2 when fed from a common source. Adjusting C_1 higher and C_2 lower from these starting values causes decreased current in Coil 1 and increased current in

Coil 2. Reversing the direction causes the current to be unbalanced in the opposite direction. The input impedance of the composite circuit remains nominally the same during the adjustment process since one leg has increased reactance while the other leg has decreased reactance.

The opposite ends of Coil 1 and Coil 2 may be terminated with an impedance Z_T. Z_T can be a common capacitor, as in conventional TCP™ systems, or an electrically short connection to the ground. Z_T could also be represented as separate capacitors terminated to the ground. If each coil has a different electrical length, the input impedance of each coil is also different. Separate terminating capacitors can be chosen so that the current maximum occurs nominally at the center of each coil length.

When two coils are symmetrically balanced, the currents flowing to each coil are nominally identical. By varying the values of C_1 and C_2, one skilled in the art will appreciate that unbalanced current flows to Coil 1 and Coil 2 are achieved. Assuming that the input reactances, X_1 and X_2, are inductive, then when C_2 is increased away from the balanced situation for example, $X_2 > X_1$, then $I_1 > I_2$. In this case, the current in the inner coil (Coil 1) is larger than the outer coil which causes stronger inductive coupling in the center of the reactor. As a result, relatively high plasma density is produced in the central region beneath Coil 1. In the alternative, the current in the outer coil (Coil 2) can be adjusted to be larger than that in the inner coil, in order to compensate for lower plasma density in an area surrounding the inner coil, such as near the reactor wall.

The use of two single-turn coils as described above is provided merely for explanatory purposes. One skilled in the art will appreciate that the general principles set forth above are equally applicable to multiple-coil, multiple-turn systems. Furthermore, the present invention is not limited to two dimensional coil configurations (as illustrated in Figure 3), but may alternatively be implemented as three dimensional coil configurations. For example, the coils can be arranged to conform to a dome-shaped dielectric window or arranged helically around a

cylindrical dielectric window. One skilled in the art will appreciate that the principles set forth above are equally applicable to domed, helical, or other three-dimensional configurations having multiple coils with multiple turns.

Figure 4 illustrates the TCP™ antenna system 400 according to a second embodiment of the present invention. In Figure 4, two multiple-turn coils (Coil 1 and Coil 2) are provided having four tuning capacitors C_1 - C_4 attached thereto. As is evident from the figure, Coil 1 is positioned in the center, while Coil 2 is preferably positioned further toward the outer edge of the reactor's top opening. The RF input is simultaneously fed to a first end of Coils 1 and 2 through tuning capacitors C_1 and C_2, respectively. The opposite ends of Coils 1 and 2 are terminated through tuning capacitors C_3 and C_4, respectively. As with the dual-coil single-turn system described above with respect to Figure 3, the two coils effectively generate a more gradual toroidal-shaped plasma. Since the currents I_1 and I_2 flow in the same direction, the power couplings to the plasma from the coils spread out over the entire region and produce a single flattened toroidal-shaped plasma. If the currents are unbalanced, the toroidal field can be stronger in the center or at the outside.

Two capacitors are provided for each coil so as to obtain a more symmetric current distribution along the coil. For example, one can adjust C_1 together with C_3 so that the current maximum (as well as the purely resistive impedance point) occurs at the center of Coil 1. Moving from the center of the coil towards C_1, the reactance is inductive, and moving from the center of the coil towards C_3 the reactance becomes capacitive, so that the current is maximum in the center and is reduced away from the center in a nominally sinusoidal fashion.

Furthermore, adjustments of C_3 and C_4 can compensate for the azimuthal non-uniform plasma described above. For example, one can adjust C_3 to achieve the maximum current at point P_1 of Coil 1 in Figure 4. As a result, the power coupling to the plasma is higher beneath P_1 and the corresponding plasma density is higher. This tends to lead toward azimuthal non-uniformity. However, by

adjusting C_4, the maximum current can be achieved at location P_2 in Coil 2 along the same radial axis opposite P_1. Therefore, a higher power coupling of Coil 2 at P_2 offsets the effect due to Coil 1, resulting in a more azimuthally uniform plasma. As an alternative to adjusting C_3 and C_4, the azimuthal position of Coil 1 can be physically rotated relative to that of Coil 2, so that the current maxima in Coil 1 and Coil 2 occur at P_1 and P_2, respectively.

According to an exemplary embodiment of the present invention, the tuning capacitors, C_1 and C_2, can be arranged such that they turn in opposite directions with a single control. In this way, the current unbalance and hence, plasma uniformity, can be optimized with a single control from a single generator without disturbing the single conventional matching network at the input. Similarly, adjusting C_3 and C_4 in opposite directions can have the same effect as adjusting C_1 and C_2.

As the number of turns in the coils varies, the mutual coupling between the coil and the plasma changes in a manner similar to the mutual coupling between the primary coil (i.e., the driving coil) and secondary coil (i.e., the plasma) of a transformer (see Albert J. Lamm, "Observations of Standing Waves on an Inductive Plasma Coil Modeled as a Uniform Transmission Line," J. Vac. Sci. Tech. A, Vol. 15, No. 5, Sept./Oct. 1997, p. 2615). An increase/decrease in the number of turns affects the density of the plasma. For example, an increase in the number of turns can cause a reduction in the mutual coupling coefficient which thereby lowers the plasma density. On the other hand, if the coil length is decreased, the overall plasma generation integrated over the coil length can be reduced. Therefore, one skilled in the art will appreciate that it is possible to optimize the number of turns and the overall length of each coil in order to balance these two factors.

In order to illustrate the effect of varying the values of the input tuning capacitors C_1 and C_2, the following three situations are considered: an initial situation where the value of C_1 is larger than that of C_2, a second situation where

the values of C_1 and C_2 are adjusted so that they are equal, and a final situation where the value of C_1 is less than that of C_2.

The complex propagation constant ($k = \alpha + j\beta$) for a TCP™ coil antenna can be deduced from the voltage and current waveform measurements at the input and output of the coil antenna (see Lamm). For purposes of discussion, α, β and the effective characteristic impedance Zo are assumed to be the same throughout the three situations. Table I provides the values for α, β, Zo, the electrical length of each coil, and C_1 - C_4.

Table I Dual-Coil Antenna Circuit as a lossy transmission line - Case (a)

	α=6.89x10^{-4}/degree	β=1.145 degree/in	Zo=110Ω	
	Input Capacitors (pF)	Length (degrees)	Output Capacitors (pF)	Z_{in} (Ω)
Coil 1	C_1=615.2	45	C_3=257.6	4.0+j26.4
Coil 2	C_2=415.2	45	C_4=257.6	4.0+j17.2

In Table I, Z_{in} represents the input impedance of each coil. The overall input impedance of the two coils is 2.1 +j 10.5 Ω which is approximately half of Z_{in} for each coil. Table II lists the magnitudes and phase angles of I_i, I_i', V_i, and V_i' for the i-th coil when an input RF power of 1000 W and the parameters described in Table I are provided. In Table II, I_i represents the current at the input end (closer to RF input in Figure 4) of the i-th coil (i = 1, 2), I_i' represents the current at the output end (closer to C_3 and C_4 in Figure 4) of the i-th coil, and V_i and V_i' represent the voltage at the input and the output ends of the i-th coil, respectively.

Table II The RF currents and voltages at the input and the output of the two coils

	Input Current		Output Current		Input Voltage		Output Voltage	
i-th coil	(I_i)rms	Angle	(I_i')rms	Angle	(V_i)rms	Angle	(V_i')rms	Angle
Coil 1	8.7 A	-3°	8.7A	-3°	399V	+82°	398V	-93°
Coil 2	13.2 A	+2°	13.2A	+1°	603V	+87°	601V	-89°

As is evident from Table II, the RF current and voltage are unbalanced between the two coils, but are balanced within each coil. Both the current and voltage in the inner coil (Coil 1) are 34% less than those in the outer coil (Coil 2) since the overall impedance of the inner coil is higher than that of the outer coil. Each coil is symmetrically balanced around the coil center, so that the values of the input current and voltage in each coil are almost equal to the output values in magnitude. Away from each coil's center the impedance is inductively-dominated toward the input end of the coil and capacitively-dominated toward the output end; this is evident from the phase angle change between the input and output voltage.

The effect of varying the values of C_1 and C_2 (so that $C_1 = C_2$) on the currents I_1 and I_2 is set forth in Tables III and IV below.

Table III Dual-Coil Antenna Circuit as a lossy transmission line - Case (b)

	α=6.89x10^{-4}/degree	β=1.145 degree/in	Zo=110Ω	
	Input Capacitors (pF)	Length (degrees)	Output Capacitors (pF)	Z_{in} (Ω)
Coil 1	C_1=515.2	45	C_3=257.6	4.0+j22.7
Coil 2	C_2=515.2	45	C_4=257.6	4.0+j22.7

The overall input impedance of the two coils is 2.0 +j11.4Ω which is approximately half of Z_{in} for each coil. Table IV lists the magnitudes and phase

angles of I_i, I_i', V_i, and V_i' for the i-th coil when an input RF power of 1000 W and the parameters described in Table III are provided.

Table IV The RF currents and voltages at the input and the output of the two coils

	Input Current		Output Current		Input Voltage		Output Voltage	
i-th coil	(I_i)rms	Angle	(I_i')rms	Angle	(V_i)rms	Angle	(V_i')rms	Angle
Coil 1	11.2 A	0°	11.2 A	-1°	511V	+85°	510V	-91°
Coil 2	11.2 A	0°	11.2 A	-1°	511V	+85°	510V	-91°

Since $C_1 = C_2$ and $C_3 = C_4$, and Coil 1 is identical to Coil 2, the RF current and voltage are balanced between the two coils as well as within each coil.

The final situation illustrates the effect of varying the values of C_1 and C_2 such that the value of C_1 is less than that of C_2.

Table V Dual-Coil Antenna Circuit as a lossy transmission line - Case (c)

	$\alpha = 6.89 \times 10^{-4}$/degree	$\beta = 1.145$ degree/in	$Zo = 110\Omega$	
	Input Capacitors (pF)	Length (degrees)	Output Capacitors (pF)	Z_{in} (Ω)
Coil 1	$C_1 = 415.2$	45	$C_3 = 257.6$	4.0+j17.2
Coil 2	$C_2 = 615.2$	45	$C_4 = 257.6$	4.0+j26.4

The overall input impedance of the two coils is 2.1 +j10.5Ω which is approximately half of Z_{in} for each coil. Table VI lists the magnitudes and phase angles of I_i, I_i', V_i, and V_i' for the i-th coil when an input RF power of 1000 W and the parameters described in Table V are provided.

Table VI The RF currents and voltages at the input and the output of the two coils

	Input Current		Output Current		Input Voltage		Output Voltage	
i-th coil	(I_i)rms	Angle	(I_i')rms	Angle	(V_i)rms	Angle	(V_i')rms	Angle
Coil 1	13.2 A	+2°	13.2 A	+1°	603V	+87°	601V	-89°
Coil 2	8.7 A	-3°	8.7 A	-3°	399V	+82°	398V	-93°

In this case, both the RF current and voltage in the inner coil (Coil 1) are 51% greater than those in the outer coil (Coil 2).

It is evident from the above situations that, by only varying C_1 and C_2, the current as well as the voltage in a coil can be adjusted substantially with respect to the current and voltage in the other coil.

Figure 5 illustrates a third embodiment of the present invention. In Figure 5, a helical coil, in addition to two multiple-turn coils and four tuning capacitors C_1 - C_4, is provided. According to this embodiment, the inner coil (Coil 1) consists of two parts. Part I represents the planar multiple-turn coil described above with respect to Figure 4. Part II represents a helical coil which is placed vertically with respect to the planar multiple-turn coil and has an axis identical to the axis of the planar coils (Part I of Coil 1 and Coil 2).

In this embodiment, the electrical length for the inner coil is increased so that Coil 1 and Coil 2 are more balanced in terms of their electrical lengths. When two electrical lengths are close to each other, the current to each coil can be adjusted to a greater extent while maintaining a more constant composite input impedance. The helical coil, according to the present invention, aids in the inductive coupling to the plasma in the center. Although the E-field generated by the helical coil is also azimuthal and is zero in the center, the mean radius of this azimuthal E-field is in the order of the diameter of the helical coil. As a result, the plasma in the center can be made more dense to provide better overall uniformity.

The cylinder in the middle of the helical coil is made of a dielectric material and can be either solid in which case the cylinder merely provides mechanical support for the helix or hollow along its axis. In the latter case, the hollow cylinder is vacuum sealed on the top end and opened on the bottom end so that the hollow section of the cylinder is directly connected to the chamber. In such a case, the process gas is introduced not only to the vacuum chamber, but also to the hollow cylinder. The cylinder would be considered to be part of the dielectric window of the plasma reactor. The plasma density in the hollow cylinder can be higher than that in the chamber due to a relatively strong induced field and the hollow cathode effect. The plasma which is remotely produced in the hollow cylinder diffuses into the chamber's center. Moreover, relatively high voltage can be adjusted by the termination capacitor C_3, such that discharge can be easily struck at a low pressure regime, typically less than 10m-Torr.

Figure 6 illustrates a fourth embodiment of the present invention. According to this embodiment, each coil (Coil 1 and Coil 2) consists of two parts. Part 1 is configured as a planar multiple-turn coil while Part 2 is configured as a helical coil, which is placed vertically with respect to the planar multiple-turn coil (i.e., Part 1) and has an axis identical to the axis of Part 1.

The input radio frequency enters the antenna system 600 through the planar multiple-turn coils in Coil 1 and Coil 2, and exits through the helical coils, such that the current flows in the same direction in both coils. In order to have comparable electrical lengths for Coil 1 and Coil 2, the helical coil (Part 2) in Coil 2 preferably has the same radius as that of the most inner turn of the planar multiple-turn coil (Part 1 of Coil 2), while the helical coil (Part 2) in Coil 1 preferably has the same radius as that of the most outer turn of the planar multiple-turn coil (Part 1 of Coil 1). The number of turns of the helical coils in Coil 1 and Coil 2 is selected such that the overall electrical lengths of Coil 1 and Coil 2 are substantially similar. It is evident from Figure 6 that the small openings of the split rings of Coils 1 and 2 are misaligned. While it is possible to provide a

configuration where the openings are aligned, one skilled in the art will appreciate that such a configuration would result in a lower power coupling to the plasma in the location of the openings.

The input tuning capacitors (C_1 and C_2) and the output tuning capacitors (C_3 and C_4) allow for an adjustment of the current distribution in the coils in a manner similar to that discussed above with respect to Figures 3-5. The present embodiment advantageously allows for the current in one coil to be independently adjusted. In the aforementioned embodiments set forth in Figures 3-5, the current to each coil is primarily adjusted by the input tuning capacitor which changes the input impedance. As the input impedance of one coil changes, the overall input impedance changes, since the coils are electrically connected in parallel. This will in turn not only change the current in the one coil, but also change the current in the other coil. In other words, the current adjustments of two coils are not independent. As a result, the matching network has to be re-tuned in order to compensate for such a change in the overall input impedance. This may not be practical in all applications since the tuning range of the matching network is finite and limited.

In Figure 6, the location of the current maximum in each coil can be shifted by adjusting the output capacitor to either a location in the planar multiple-turn coil (Part 1) or to a location in the helical coil (Part 2). The power coupling of the radio frequency to the plasma is relatively large when the current maximum is somewhere in the planar multiple-turn coil, since the planar coil is closer to the plasma. Similarly, if the current maximum is at a location in the helical coil, the power coupling to the plasma is weaker since the helical coil is further away from the plasma and the current drops off in the planar multiple-turn coil. Therefore, an adjustment of only the output capacitor can simultaneously change the location of the maximum current and the magnitude of the power coupling to the plasma. At the same time the output capacitor is being adjusted, the input capacitor can be adjusted in the opposite direction so as to maintain a relatively unchanged input

impedance of the coil. As a result, the overall input impedance will remain relatively unchanged. One skilled in the art will appreciate that by adjusting the input and output capacitors in this way, the current magnitude does not change substantially, but rather the current standing wave pattern in the coil shifts, which in turn effectively changes the power coupling to the plasma. As a result, plasma uniformity can be controllably maintained.

Figure 7 illustrates a dual-coil coupling system according to a fifth embodiment of the present invention. The dual-coil coupling system of Figure 7 uses parallel antenna elements. The two coils (Coil 1 and Coil 2) are symmetric and each loop of the coils consists of a half circle and a parallel antenna element. The RF is fed simultaneously to the central parallel element of each coil (closer to the parallel axis) and the other ends of the coils are tied together and terminated to the ground through capacitor C_T.

In contrast to a planar spiral coil, the parallel antenna coupling scheme always produces a relatively large E-field in the center and can therefore intrinsically improve plasma uniformity (see J. J. Chen et al., "Parallel-Antenna Transformer-Coupled Plasma Generation Systems", U.S. Patent Application no. 09/052,144, filed March 31, 1998). Similar to the conventional TCP™ coil, the plasma produced by each coil is toroidal and centered around o_1 for Coil 1, and o_2 for Coil 2. Compared with a single TCP™ coil, the radius of each plasma toroid is substantially shorter, thereby making it easier for plasma to diffuse into the center of the toroid compared to the conventional TCP™ system; the advantage of this coupling system is that there will be less variation of the RF current and voltage along each coil, since the electrical length of each coil is almost halved.

The foregoing has described the principles, preferred embodiments and modes of operation of the present invention. However, the invention should not be construed as being limited to the particular embodiments discussed above. Thus, the above-described embodiments should be regarded as illustrative rather than restrictive, and it should be appreciated that variations may be made in those

embodiments by workers skilled in the art without departing from the scope of the present invention as defined by the following claims.

CLAIMS:

1. An apparatus for generating an inductively coupled plasma, the apparatus comprising:

a plasma reaction chamber having a window forming an electro-magnetic field path into the chamber and a process gas supply configured to introduce process gas into the chamber;

a radio frequency antenna comprising at least first and second antenna segments disposed proximate the window of the chamber; and

a radio frequency source coupled to the antenna segments and configured to resonate a radio frequency current in the antenna segments,

wherein electro-magnetic fields induced by the radio frequency current are effective to pass through the window and excite and ionize the process gas to thereby generate plasma within the chamber, and

wherein said first antenna segment surrounds said second antenna segment.

2. The apparatus of claim 1, wherein a density of the generated plasma is substantially uniform within an area spanned by said at least first and second antenna segments.

3. The apparatus of claim 1, wherein each of said at least first and second antenna segments couples radio frequency power into different regions in the chamber, resulting in an overall uniform plasma in the chamber.

4. The apparatus of claim 1, wherein the at least first and second antenna segments are made of single-turn coils.

5. The apparatus of claim 1, wherein the first antenna segment is made of a single-turn coil and the second antenna segment is made of a multiple-turn coil.

6. The apparatus of claim 1, wherein the at least first and second antenna segments are made of multiple-turn coils.

7. The apparatus of claim 1, further comprising at least one input tuning capacitor for adjusting currents within said at least first and second antenna segments so as to achieve equal currents or unequal currents.

8. The apparatus of claim 7, wherein the at least one input tuning capacitor provides higher current in each antenna segment resulting in higher radio frequency power coupling to a region of plasma that is adjacent an antenna segment or provides lower current in each antenna segment resulting in lower power coupling to said region of plasma.

9. The apparatus of claim 7, wherein a pair of input capacitors are used to adjust currents in a pair of antenna segments and are arranged such that they are turned in opposite directions with a single control.

10. The apparatus of claim 1, wherein the at least first and second antenna segments are powered by a single radio frequency power source and tuned by a single matching network.

11. The apparatus of claim 1, wherein output ends of the first and second antenna segments are tied together and terminated to ground through an impedance.

12. The apparatus of claim 1, wherein output ends of the first and second antenna segments are terminated to ground through separate output fixed or variable capacitors.

13. The apparatus of claim 12, wherein each output capacitor adjusts a location of a current extreme or a voltage extreme along each antenna segment.

14. The apparatus of claim 12, wherein locations of current maxima in the first and second antenna segments are a function of a rotational position of the first antenna segment relative to the second antenna segment, and

wherein said output capacitors further adjust said locations so that the current maximum locations are approximately 180 degrees apart azimuthally and opposite to each other radially, thereby substantially reducing plasma azimuthal non-uniformity due to an azimuthal non-uniform current distribution.

15. The apparatus of claim 12, wherein a pair of output capacitors adjust currents in the first and second antenna segments and are arranged such that they are turned in opposite directions with a single control.

16. The apparatus of claim 1, wherein the first and second antenna segments are configured in a coplanar two dimensional configuration, a non-planar three dimensional configuration, or a combination thereof.

17. The apparatus of claim 1, wherein the first and second antenna segments are arranged concentrically with one of the antenna segments having a diameter smaller than another one of the antenna segments.

18. The apparatus of claim 16, wherein said three dimensional configuration is one of a dome or helical configuration.

19. The apparatus of claim 1, wherein each of the antenna segments is approximately circular in shape.

20. The apparatus of claim 1, wherein said at least first and second antenna segments are disposed proximate an exterior surface of the window of the chamber.

21. The apparatus of claim 1, wherein currents within the first and second antenna segments travel in a same azimuthal direction around said segments.

22. An apparatus for generating an inductively coupled plasma, the apparatus comprising:

a plasma reaction chamber having a window forming an electro-magnetic field path into the chamber and a process gas supply configured to introduce process gas into the chamber;

a radio frequency antenna comprising at least first and second multiple-turn antenna segments disposed proximate the window of the chamber; and

a radio frequency source coupled to the antenna segments and configured to resonate a radio frequency current in the antenna segments,

wherein electro-magnetic fields induced by the radio frequency current are effective to pass through the window and excite and ionize the process gas to thereby generate a plasma within the chamber, and

wherein said first multiple-turn antenna segment is an outer coil which surrounds said second multiple-turn antenna segment.

23. The apparatus of claim 22, wherein a density of the generated plasma is substantially uniform within an area spanned by the first and second multiple-turn antenna segments.

24. The apparatus of claim 22, wherein each of said at least first and second antenna segments couples radio frequency power into different regions in the chamber, resulting in an overall uniform plasma in the chamber.

25. The apparatus of claim 22, wherein the first multiple-turn antenna segment is configured as a planar multiple-turn coil and the second multiple-turn antenna segment has a first and second part.

26. The apparatus of claim 25, wherein said first part of the second multiple-turn antenna segment is configured as a planar multiple-turn coil and said second part of the second multiple-turn antenna segment is configured as a helical coil.

27. The apparatus of claim 26, wherein said second part further comprises a hollow dielectric cylinder within said helical coil and a hollow section of the hollow dielectric cylinder is directly connected to the process chamber.

28. The apparatus of claim 27, wherein the helical coil and the hollow dielectric cylinder are configured to allow plasma to be struck at a lower pressure in the chamber, resulting in an enhanced plasma density in the center of the process chamber.

29. The apparatus of claim 22, wherein the first multiple-turn antenna segment has a first planar part and a second non-planar part, and the second multiple-turn antenna segment has a first planar part and a second non-planar part.

30. The apparatus of claim 29, wherein said second part of the first multiple-turn antenna segment is configured as a helical coil.

31. The apparatus of claim 29, wherein said second part of the second multiple-turn antenna segment is configured as a helical coil.

32. The apparatus of claim 22, wherein an overall length of the first multiple-turn antenna segment is comparable to that of the second multiple-turn antenna segment, so that currents in the antenna segments can be adjusted to a greater extent.

33. The apparatus of claim 22, further comprising at least one input tuning capacitor for adjusting currents within said at least first and second antenna segments so as to achieve equal currents or unequal currents.

34. The apparatus of claim 33, wherein the at least one input tuning capacitor provides higher current in each antenna segment resulting in a higher radio frequency power coupling to a region of plasma that is adjacent an antenna segment or provides lower current in each antenna segment resulting in lower power coupling to said region of plasma.

35. The apparatus of claim 33, wherein a pair of input capacitors are used to adjust currents in the first and second antenna segments and are arranged such that they are turned in opposite directions with a single control.

36. The apparatus of claim 22, wherein the at least first and second antenna segments are powered by a single radio frequency power source and tuned by a single matching network.

37. The apparatus of claim 22, wherein output ends of the first and second antenna segments are terminated to ground through separate output fixed or variable capacitors.

38. The apparatus of claim 37, wherein each output capacitor adjusts a location of a current extreme or a voltage extreme along each antenna segment.

39. The apparatus of claim 37, wherein locations of current maxima in the first and second antenna segments are a function of a rotational position of the first antenna segment relative to the second antenna segment, and

wherein said output capacitors further adjust said locations so that the current maximum locations are approximately 180 degrees apart azimuthally and opposite to each other radially, thereby substantially reducing plasma azimuthal non-uniformity due to an azimuthal non-uniform current distribution.

40. The apparatus of claim 37, wherein a pair of output capacitors are used to adjust currents in the first and second antenna segments and are arranged such that they are turned in opposite directions with a single control.

41. The apparatus of claim 26, wherein an output capacitor is used to shift a location of a current maximum to either the first part or the second part of the second multiple-turn antenna segment resulting in a change in a power coupling from the multiple-turn antenna segment to the plasma.

42. The apparatus of claim 30, wherein an output capacitor is used to shift a location of a current maximum to either the first part or the second part of the second multiple-turn antenna segment resulting in a change in a power coupling from the multiple-turn antenna segment to the plasma.

43. The apparatus of claim 31, wherein an output capacitor is used to shift a location of a current maximum to either the first part or the second part of the second multiple-turn antenna segment resulting in a change in a power coupling from the multiple-turn antenna segment to the plasma.

44. The apparatus of claim 41, further comprising an input capacitor associated with said output capacitor, wherein tuning of the input capacitor results in an overall input impedance of the radio frequency being maintained relatively unchanged which allows current in one multiple-turn antenna segment not to affect current in other multiple-turn antenna segments.

45. The apparatus of claim 42, further comprising an input capacitor associated with said output capacitor, wherein tuning of the input capacitor results in an overall input impedance of the radio frequency being maintained relatively unchanged which allows current in one multiple-turn antenna segment not to affect current in other multiple-turn antenna segments.

46. The apparatus of claim 43, further comprising an input capacitor associated with said output capacitor, wherein tuning of the input capacitor results in an overall input impedance of the radio frequency being maintained relatively unchanged which allows current in one multiple-turn antenna segment not to affect current in other multiple-turn antenna segments.

47. The apparatus of claim 22, wherein the first and second antenna segments are arranged concentrically with one of the antenna segments having a diameter smaller than another one of the antenna segments.

48. The apparatus of claim 22, wherein said at least first and second antenna segments are disposed proximate an exterior surface of the window of the chamber.

49. The apparatus of claim 22, wherein currents within the first and second antenna segments travel in a same azimuthal direction around said segments.

50. An apparatus for generating an inductively coupled plasma, the apparatus comprising:

a plasma reaction chamber having a window forming an electro-magnetic field path into the chamber and a process gas supply configured to introduce process gas into the chamber;

a radio frequency antenna comprising two similarly-shaped antenna segments disposed proximate the window of the chamber; and

a radio frequency source coupled to the antenna segments and configured to resonate a radio frequency current in the antenna segments,

wherein electro-magnetic fields induced by the radio frequency current are effective to pass through the window and excite and ionize the process gas to thereby generate plasma within the chamber, and

wherein the two antenna segments are spaced apart and placed symmetrically about a central axis.

51. The apparatus of claim 50, wherein each antenna segment is D-shaped and configured as a half circle and a straight line approximately along its diameter.

52. The apparatus of claim 51, wherein the straight lines of said antenna segments are parallel to each other and cover a central region of the window resulting in symmetric plasma densities around the central axis.

53. The apparatus of claim 50, wherein input ends of the two antenna segments are tied together, and output ends of the two antenna segments are tied together and terminated to ground through a variable capacitor.

54. The apparatus of claim 51, wherein currents in the straight lines of the two antenna segments travel in a same direction.

55. The apparatus of claim 50, wherein the antenna segments are powered by a single radio frequency power source and tuned by a single matching network.

56. The apparatus of claim 50, wherein a density of the generated plasma is substantially uniform within an area spanned by said antenna segments.

57. The apparatus of claim 50, wherein each of said antenna segments couples radio frequency power into different regions of the chamber, resulting in an overall uniform plasma in the chamber.

58. The apparatus of claim 50, wherein said antenna segments are disposed proximate an exterior surface of the window of the chamber.

59. An inductively coupled plasma antenna system for a plasma reaction chamber comprising:

first and second concentric current paths which are spaced apart,

wherein current within the concentric current paths travel in a same direction.

60. The system of claim 59, wherein the concentric current paths couple radio frequency power into different regions radially and azimuthally in the chamber and cooperate to provide a uniform plasma distribution in the chamber.

61. The system of claim 59, wherein the concentric current paths are configured in a coplanar two dimensional configuration, a non-planar three dimensional configuration, or a combination thereof.

62. A process of processing a semiconductor substrate by contacting an exposed surface of the semiconductor substrate with the plasma formed in the apparatus of claim 1.

63. A process of processing a semiconductor substrate by contacting an exposed surface of the semiconductor substrate with the plasma formed in the apparatus of claim 22.

64. A process of processing a semiconductor substrate by contacting an exposed surface of the semiconductor substrate with the plasma formed in the apparatus of claim 50.

65. A process of processing a semiconductor substrate by contacting an exposed surface of the semiconductor substrate with the plasma formed in the apparatus of claim 59.

A radio frequency plasma multiple–coil antenna allows for controllable, uniform inductive coupling within a plasma reactor. According to exemplary embodiments, multiple coils are positioned on a dielectric window of a plasma chamber, and are powered by a single radio frequency generator and tuned by a single matching network. Each coil is either planar or a combination of a planar coil and a vertically stacked helical coil. The input end of each coil is connected to an input tuning capacitor and the output end is terminated to the ground through an output tuning capacitor. The location of the maximum inductive coupling of the radio frequency to the plasma is mainly determined by the output capacitor, while the input capacitor is mainly used to adjust current magnitude into each coil. By adjusting the current magnitude and the location of the maximum inductive coupling within each coil, the plasma density in different radial and azimuthal regions can be varied and controlled, and therefore, radially and azimuthally uniform plasma can be achieved.

【図7】

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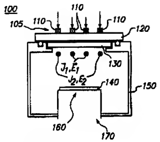

FIG. 1

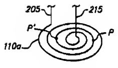

FIG. 2A

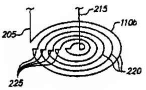

FIG. 2B

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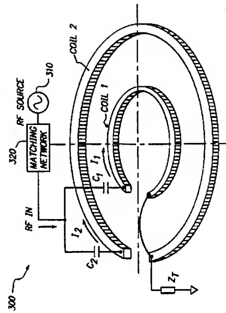

FIG. 3

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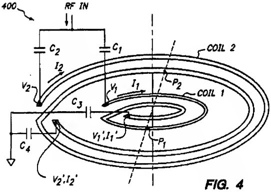

FIG. 4

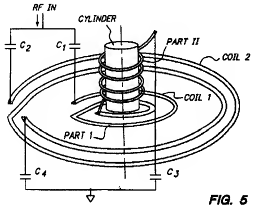

FIG. 5

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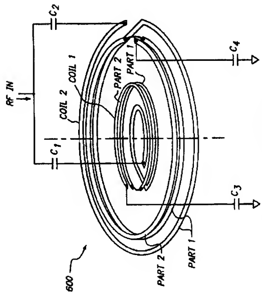

FIG. 6

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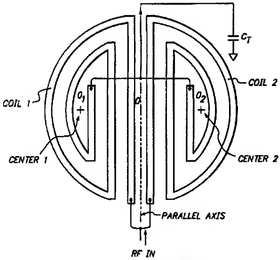

FIG. 7